PARALLEL STRUCTURED/UNSTRUCTURED SIMULATION OF MISSILE DYNAMIC FLOWFIELDS

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INTRODUCTION

- **Focus of our work is high-fidelity, unsteady/transient simulations of problems related to missile dynamics**
  - **Dynamic multi-body motion**
  - **Aeroacoustic control using LES simulations**
  - **High speed gas/liquid interaction problems**

- **Tools used are:**

  CRAFT: Structured, high-accuracy solver

  CRUNCH: Multi-Element, unstructured solver for dynamic grid motion

RELEVANT FEATURES OF CRAFT CFD NAVIER-STOKES CODE

NUMERICS/ PARALLEL PROCESSING	• 1D/2D/AXI/3D Finite-Volume Discretization
	• Implicit, ADI and L/U, Higher-Order Upwind (Roe/TVD) Formulation
	• Fully Implicit Source Terms/Boundary Conditions
	• PNS Spatial Marching Capability
	• Domain-Decomposition Parallel Architecture with MPI
	• Shared Memory Parallelism
	• Preconditioning Extensions
GRID FEATURES	• Grid Dynamics to Account for Moving Boundaries
	• Grid Patching/Blanking for Complex Geometries
	• Solution-Adaptive Gridding and Grid Embedding
	• Noncontiguous Grid Interfacing with Flux Preservation Across Domains
THERMO-CHEMISTRY	• Multi-Component Real Gas Mixtures
	• Finite-Rate Chemistry/Arbitrary Number of Species and Reactions
	• Fully Implicit Source Term Linearization
MULTIPHASE FLOW	• Nonequilibrium Particle/Droplet Solvers (Eulerian and Lagrangian Formulations)
TURBULENCE	• k-ε /EASM Formulations with Compressibility/Vortical Upgrades
	• LES Subgrid Scale Models – Algebraic and One-equation

RELEVANT FEATURES OF CRUNCH CFD NAVIER-STOKES CODE

NUMERICS	• Finite-Volume Roe/TVD Flux Construction, Vertex Storage
INTEGRATION	• Explicit Four-Step Runge-Kutta, Implicit GMRES, Gauss-Seidel
GRID ELEMENTS	• Tetrahedral, Hexahedral, Prismatic, Pyramid
PARALLEL PROCESSING CAPABILITIES	• Domain Decomposition MPI, Independent Grids with Noncontiguous Interfacing, Automated Load Balancing
DYNAMIC GRID CAPABILITIES	• Node Movement Solver (Implicit Elasticity Approach), Automated Embedding, Sliding Interfaces
GRID ADAPTION	• Variable Element Grid Refinement using Delaunay and cell subdivision Procedures, Automated Load Balancing of Adapted Grid
THERMOCHEMISTRY	• Multi-component Real Gas Mixtures, Finite-Rate Kinetics
TURBULENCE RANS/LES	• k-ε /EASM Formulations with Compressibility/Vortical Upgrades • LES Subgrid Scale Models – Algebraic and One-equation • Algebraic (Smagorinsky) and Single Equation (k) SGS Models
MULTIPHASE FLOW	• Nonequilibrium Particle/Droplet Solvers (Eulerian and Lagrangian Formulations)

DYNAMIC MULTI-BODY PROBLEMS

- Simulation of large scale separation scenarios accomplished through:
  - Mesh movement – allowing the unstructured grid to deform a certain extent
  - Mesh adaption – localized coarsening and refinement to correct distorted regions of the grid

- High performance computing / parallel issues:
  - Number of processors to simulate transient flow over realistic, complex geometries
  - 100-200 hours on 32-64 CPUs typical
  - Dynamic load balancing as the mesh is adapted and changes size is a key driver in simulation efficiency

MESH MOVEMENT

- **Mesh represented as linearly elastic solid**
- **Equations of elasticity solved to propagate stresses created by motion of boundary surfaces**
  - **More robust than spring analogy technique**
  - **Velocity of nodes computed to update interior points**
- **Node movement performed in parallel**
  - **Velocity at interprocessor nodes broadcast to all processors**
  - **Subiteration to ensure adequate propagation of stresses**

CRISP MESH ADAPTION CODE OVERVIEW

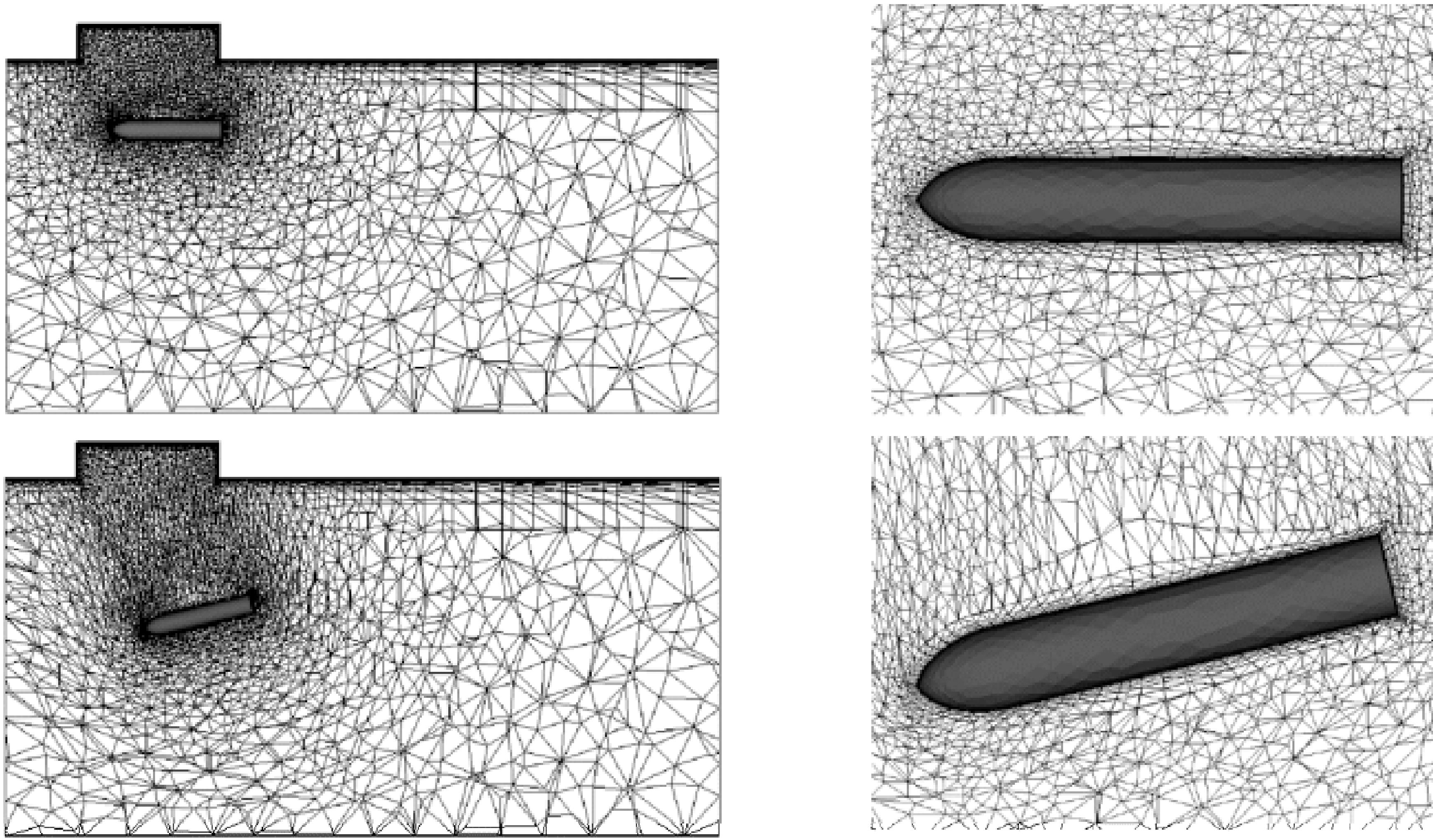
- **A localized mesh adaptation code for tetrahedral or mixed tet/prism grids**
- **Enrichment of tetrahedra using Delaunay refinement procedure**
- **Coarsening accomplished by collapsing edges from the grid**
- **Mesh modification driven by modifying point spacing through cell quality and/or solution gradient criteria**
- **Recently extended to include refinement of mixed element grids with hexahedral regions**

MESH DEFORMATION MATRIX ANALYSIS

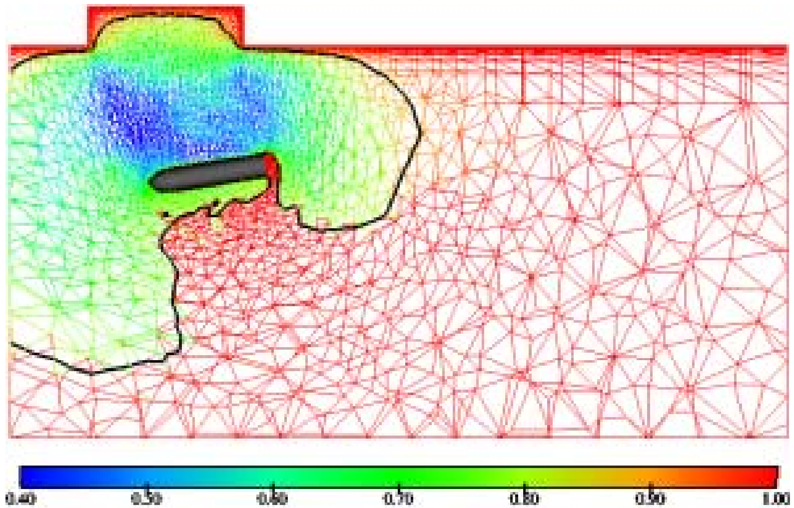
$$[A]=[P][U]$$

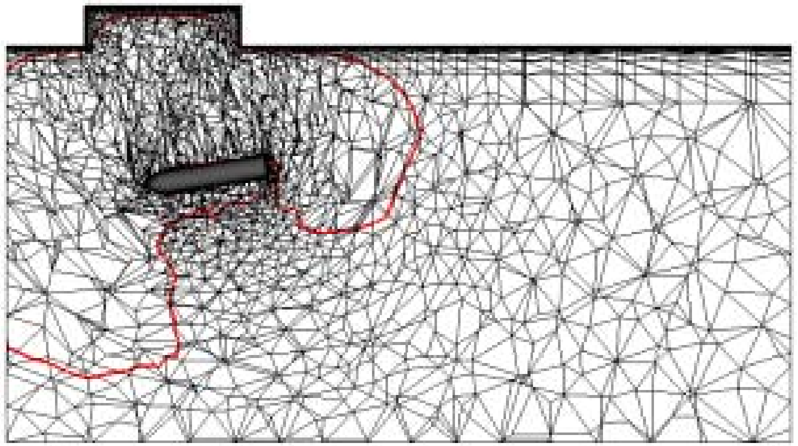
- The element is transformed from time t_0 to t_1 through a deformation matrix [A]
- This deformation can be decomposed into rigid body modes and deformation modes $$[A]=[P][U]$$
  - If the element rotates without deforming, [P] is the identity matrix
  - If the element deforms without rotating, [U] is the identity matrix
- Eigenvalues of [P] provide useful information on element deformation and quality
  - Represent dilatation of the cell in each of three principal directions
  - Ratio of min/max eigenvalues (condition number) denotes extent of deformation
- These values may be used to directly drive mesh modifications

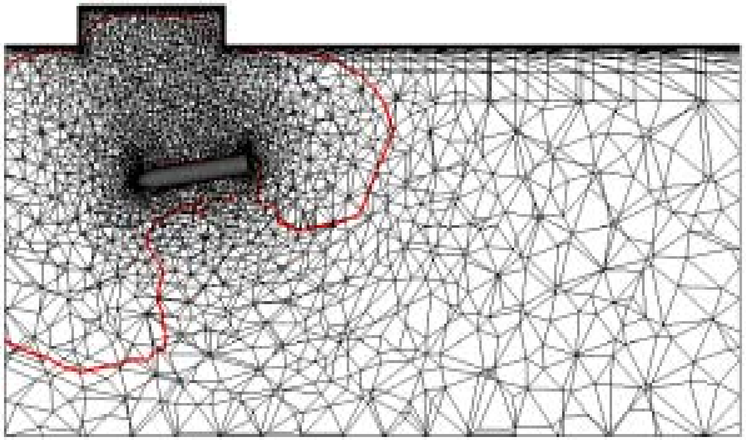
VISCOUS GRID MOTION FOR PRESCRIBED STORE TRAJECTORY



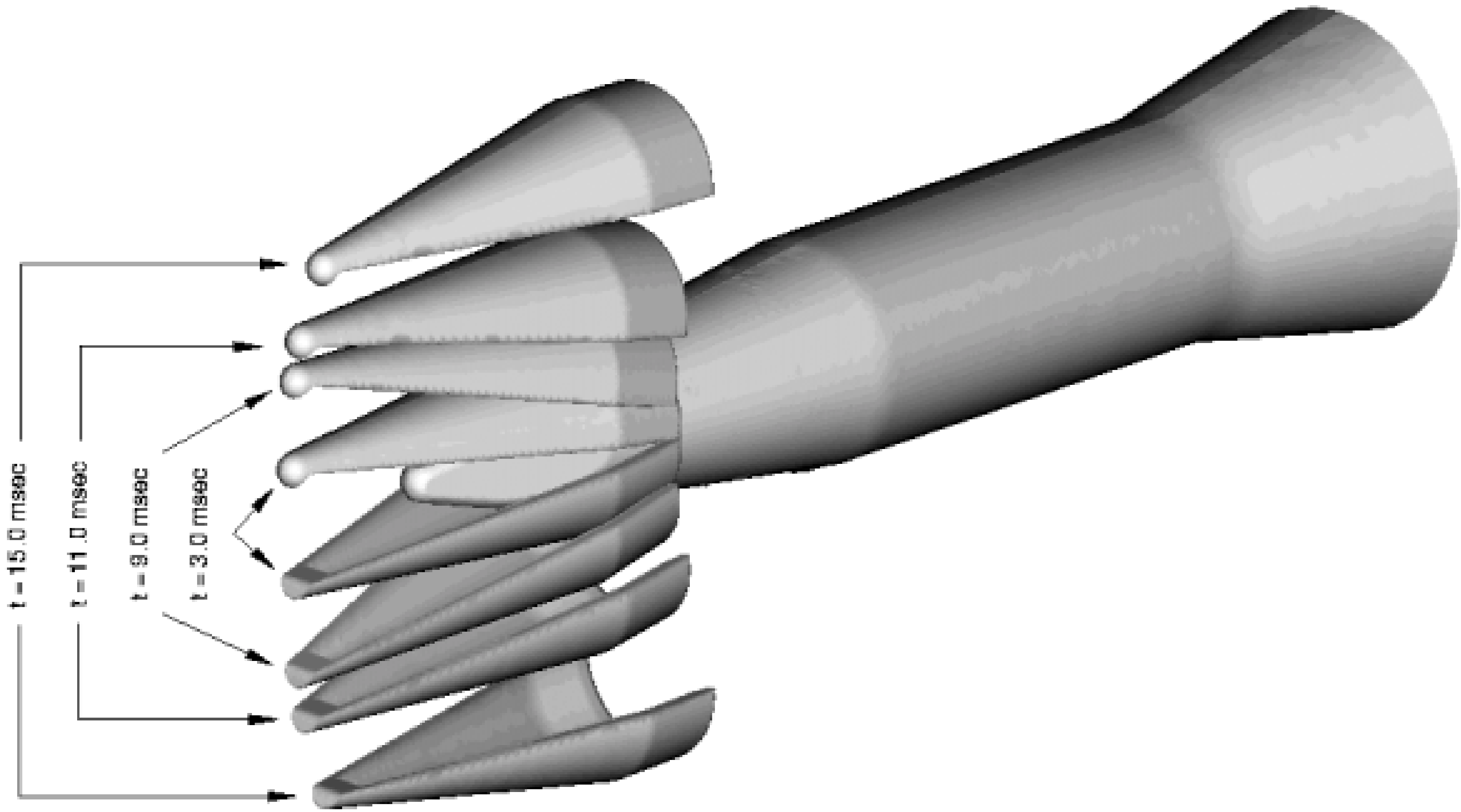
USE OF MATRIX CONDITION NUMBER IN DYNAMIC MESH ADAPTATION



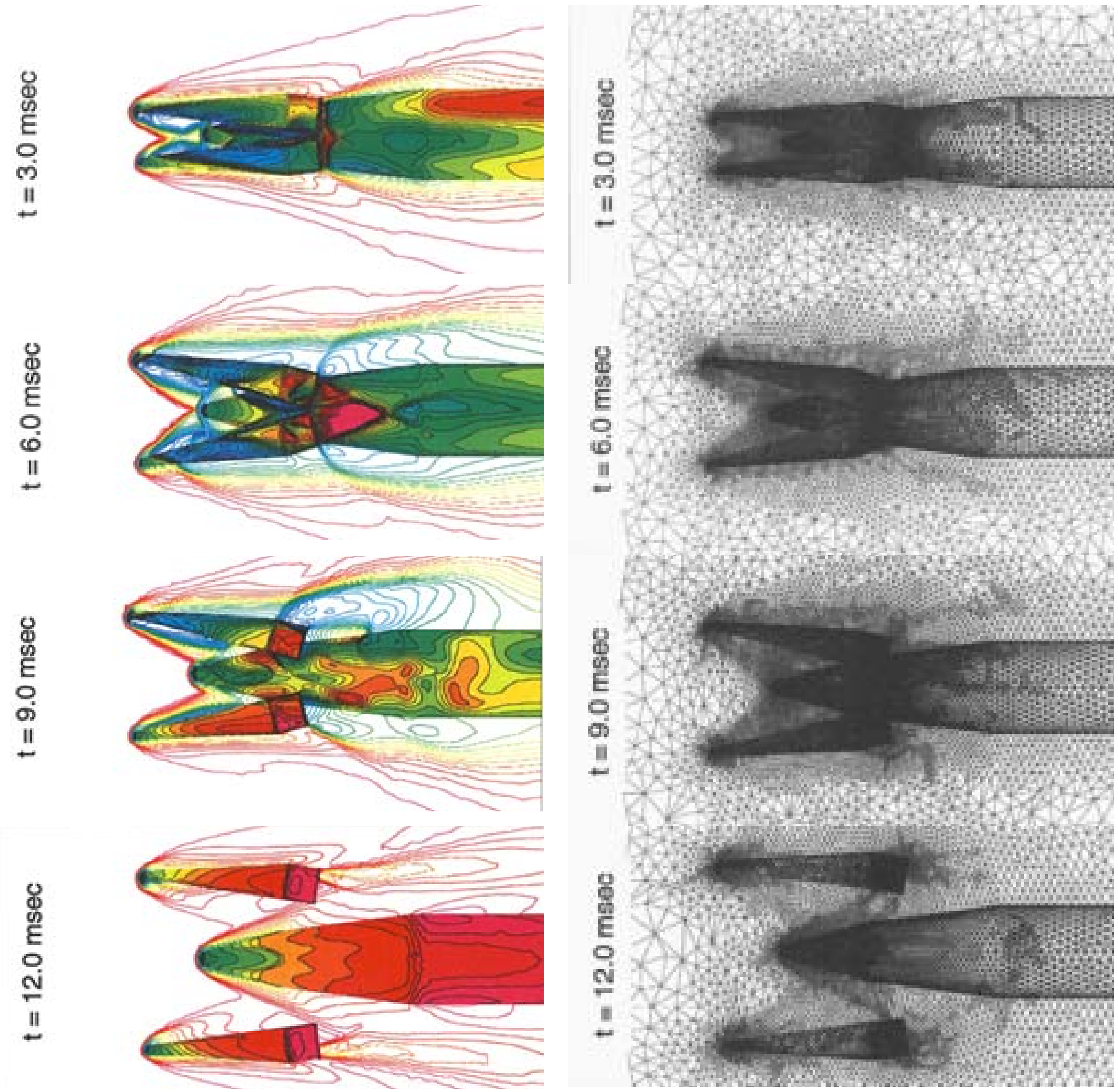




OVERVIEW OF AIT SHROUD DEPLOYMENT



SHROUD SEPARATION, MACH NUMBER CONTOURS AND COMPUTATIONAL MESHES



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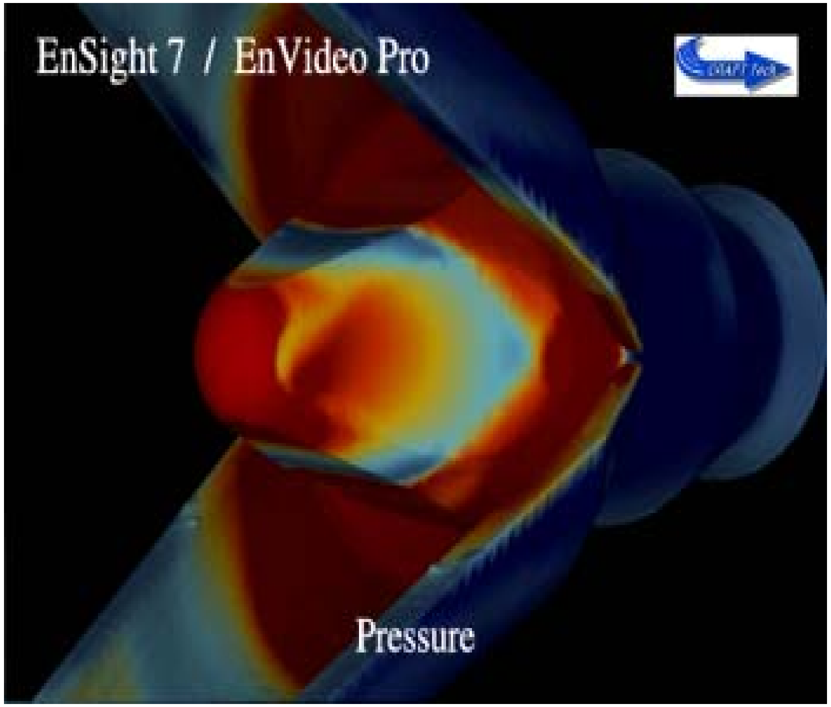
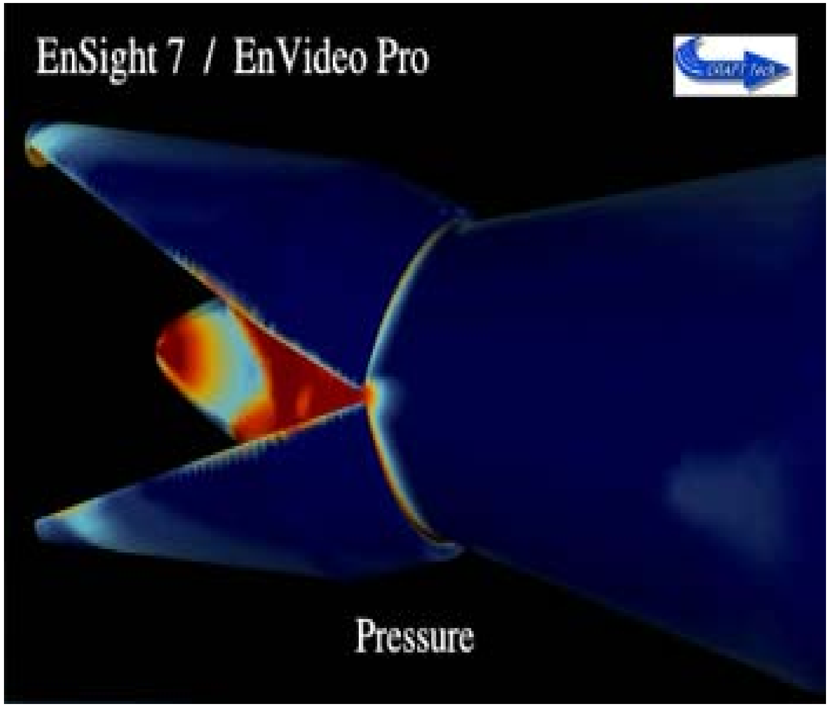
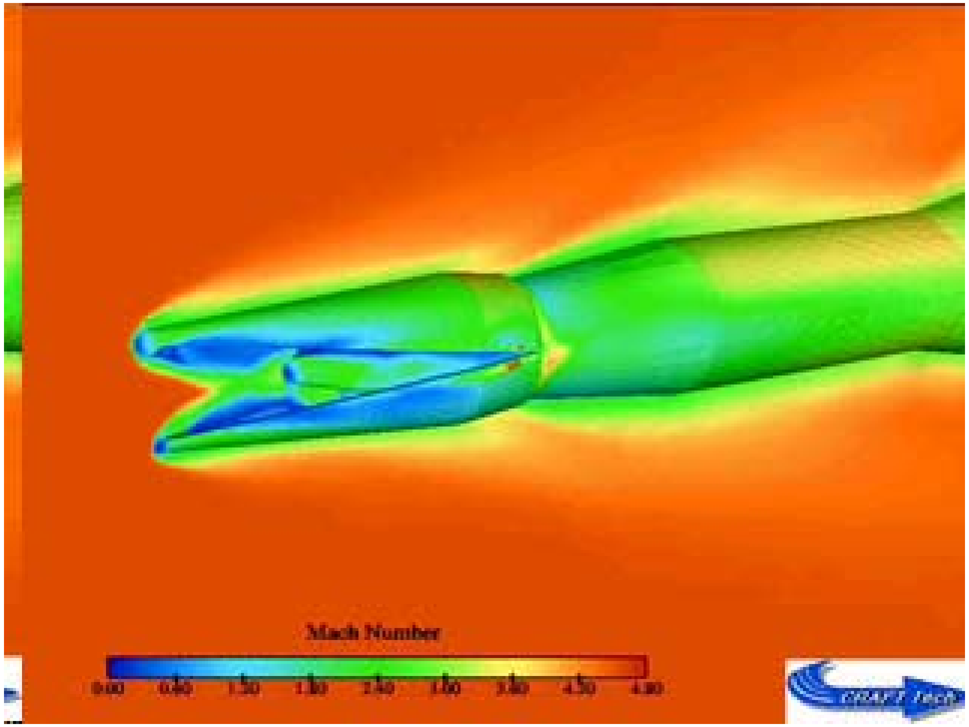
SHROUD SEPARATION, PRESSURE CONTOURS





SHROUD SEPARATION, MACH NUMBER CONTOURS

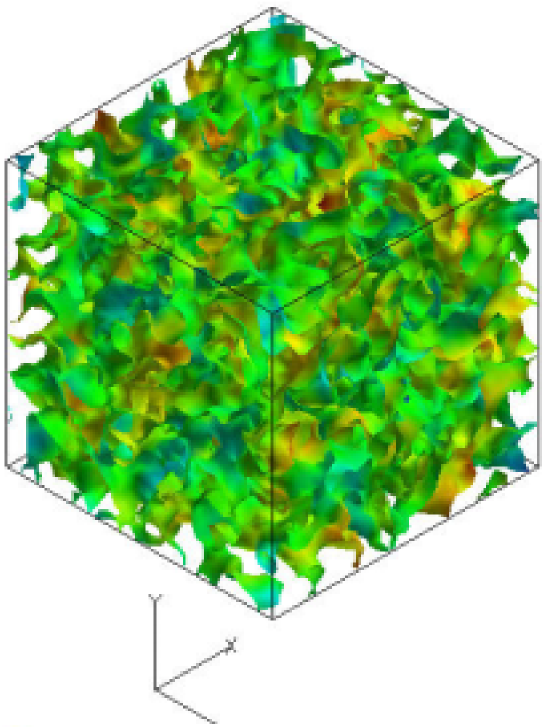


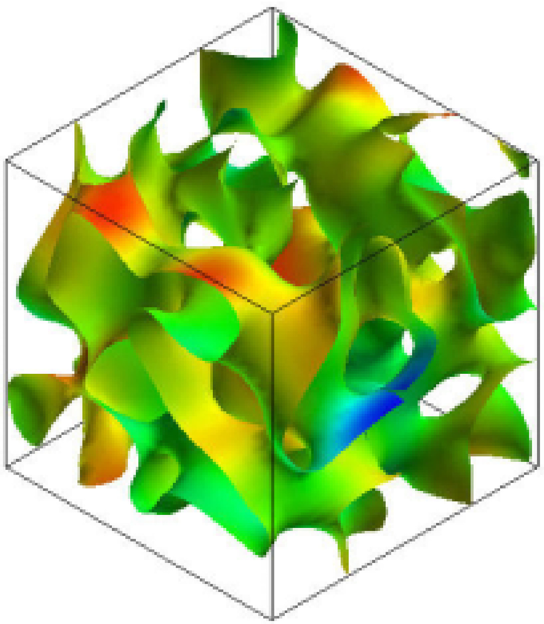
LES OF HIGH SPEED FLOWS

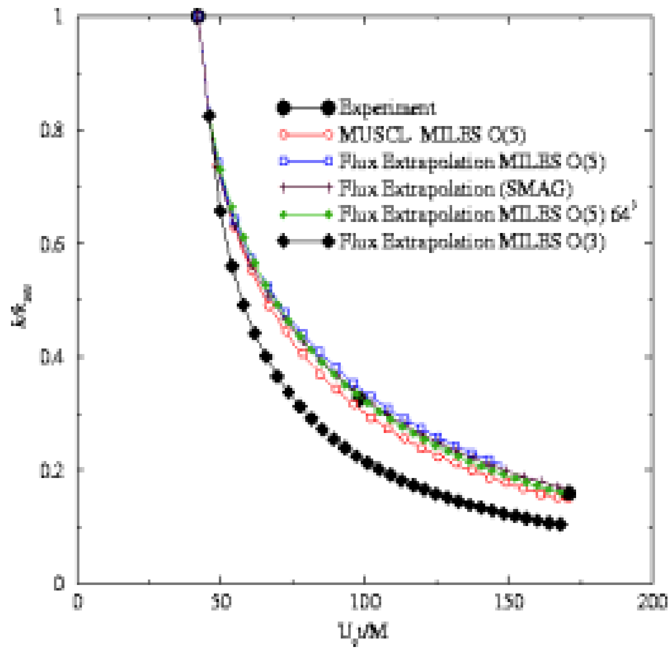
- Unsteady dynamics
  - Aeroacoustics
  - Dynamic loading on aero-vehicles
- Numerical Methods
  - Schemes should handle fine scale turbulence and Shocks
  - Non-Dissipative Flux integration scheme
    - Fifth Order Scheme of Rai (1987)
    - Roe Flux construction
  - Shock/ Discontinuity Handling
    - Jameson type 2nd order term
    - Triggered by switch
    - Operates only at strong discontinuities

NUMERICAL METHODS

- Validation : LES of isotropic turbulence
  - Experiment of Comte-Bellot & Corrsin

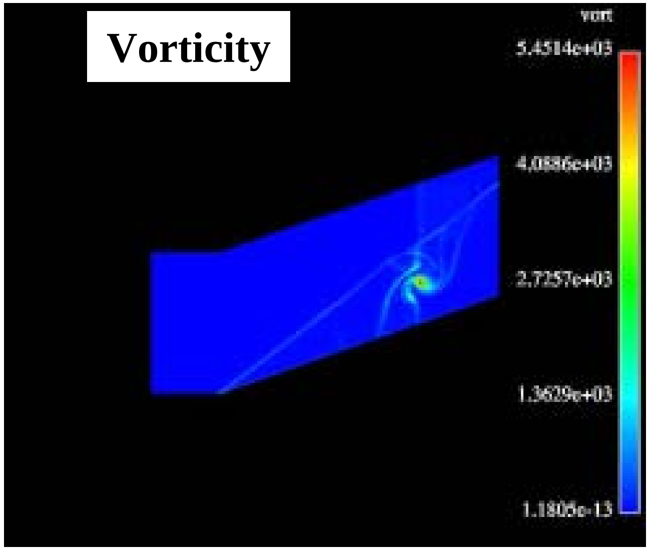


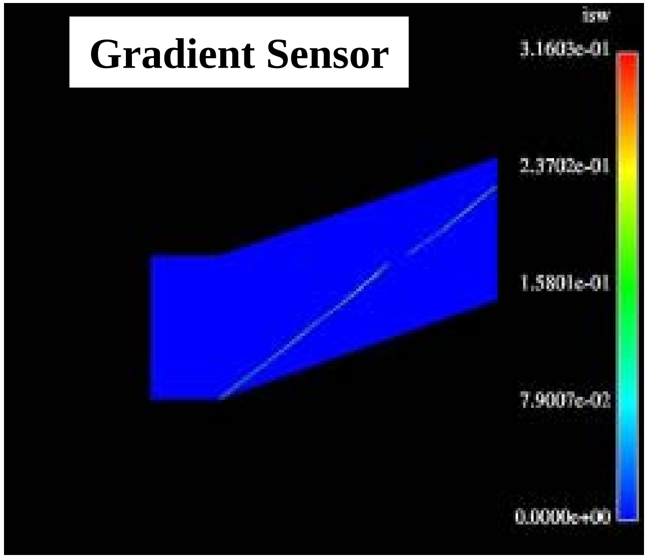




Numerical Methods

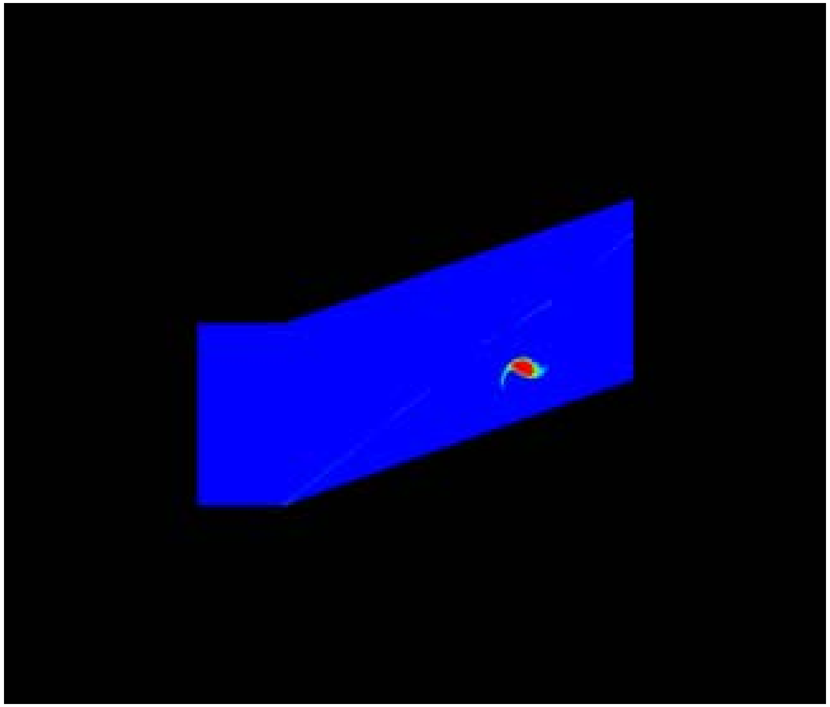
- Validation : Shock Vortex Interaction
  - Switch triggers only along shock
  - Vortex Strength is preserved

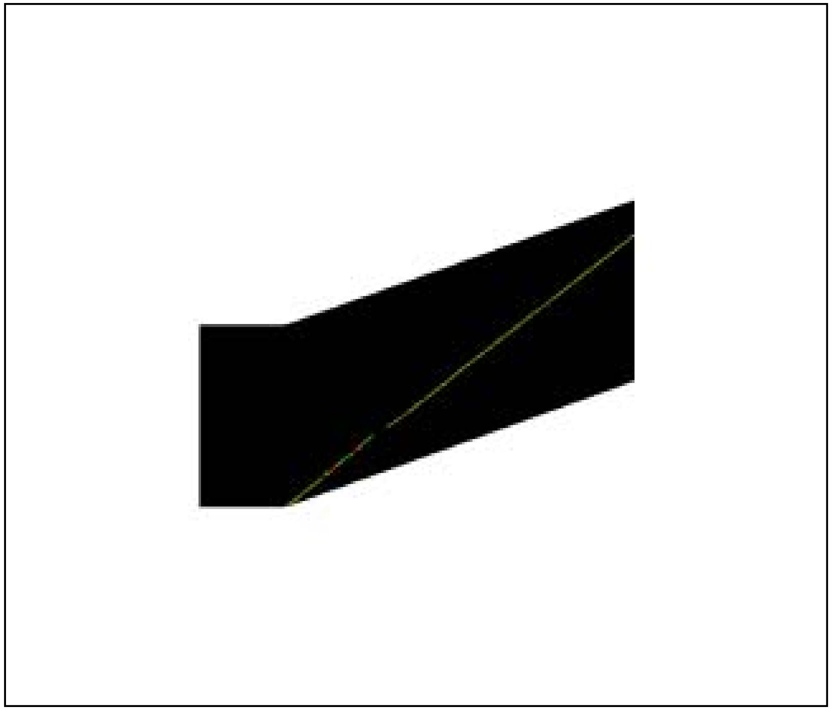




Shock-Vortex Interaction

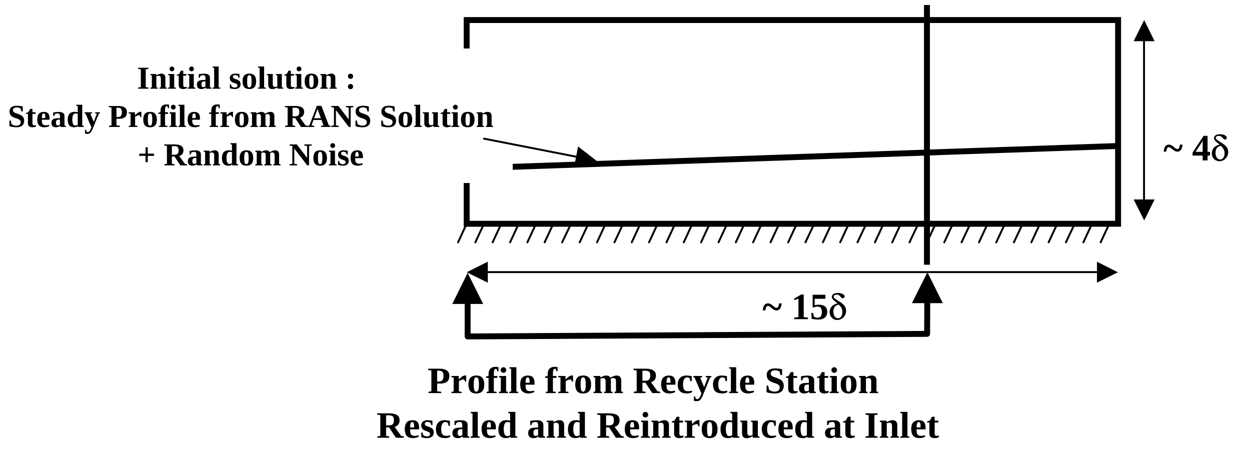
Numerical Methods



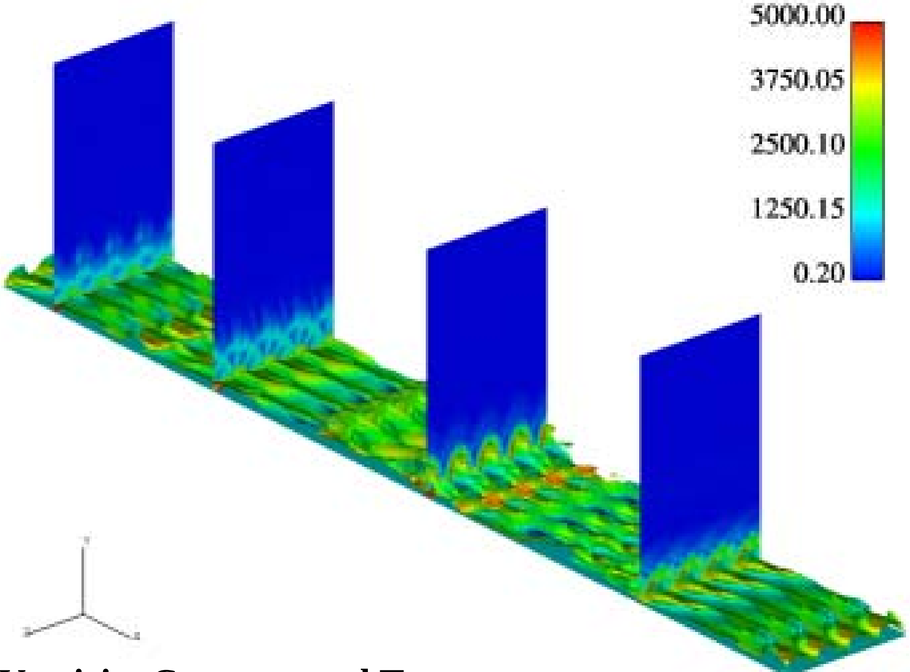


LARGE EDDY SIMULATIONS : COMPRESSIBLE BOUNDARY LAYERS

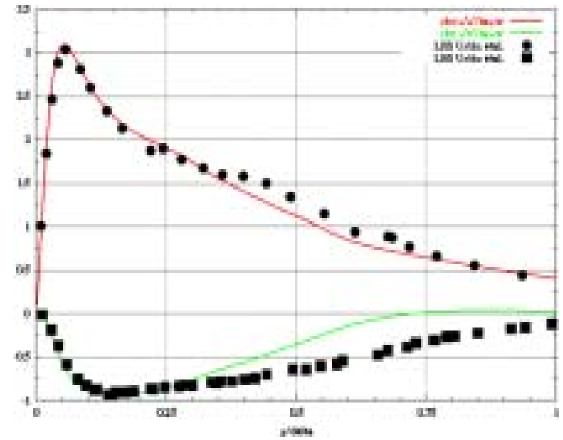
- High speed boundary layers
  - M~3.0-4.0
  - Re_δ = 20,000-100,000
  - "Recycling" method for boundary conditions



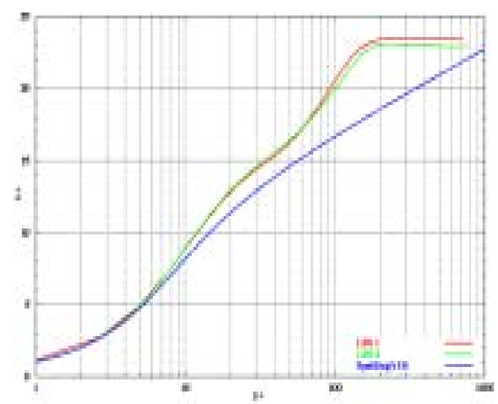
LARGE EDDY SIMULATIONS : COMPRESSIBLE BOUNDARY LAYERS



Vorticity Contours and Temperature Isosurface colored by *w*

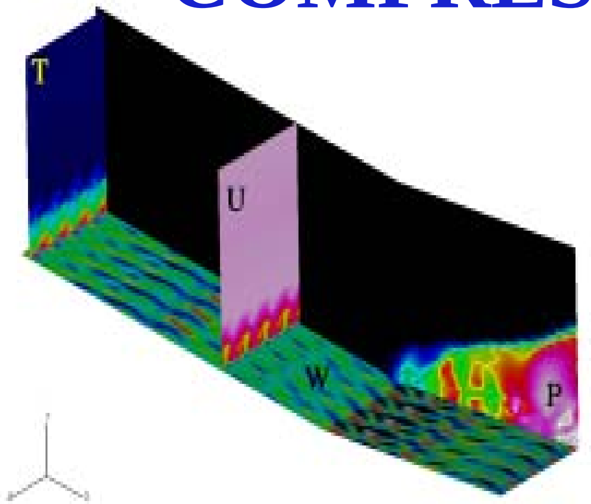


Reynolds normal and shear stress

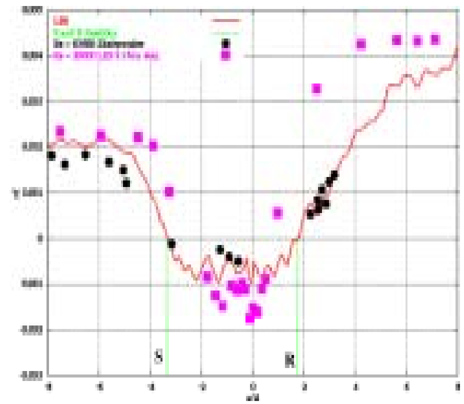


Mean U velocity with Van-Driest transformation

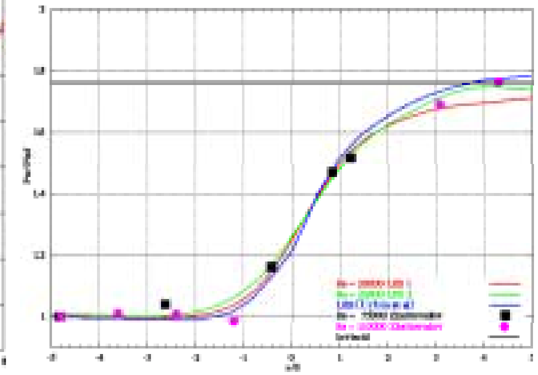
LARGE EDDY SIMULATIONS : COMPRESSION CORNER FLOWS



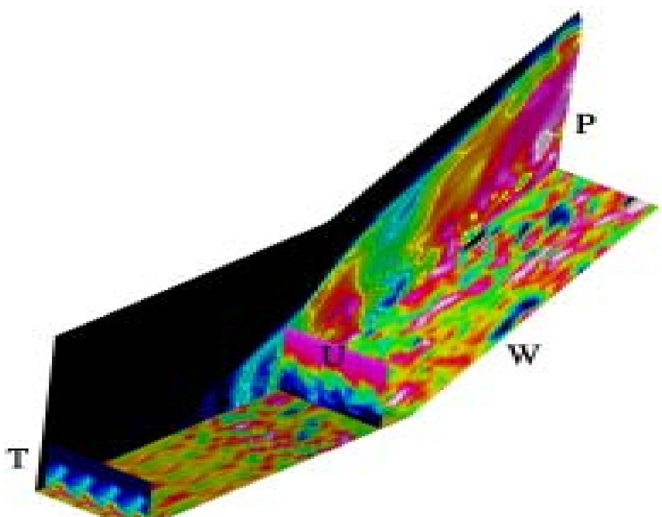
Instantaneous contours in the flow field (8˚)



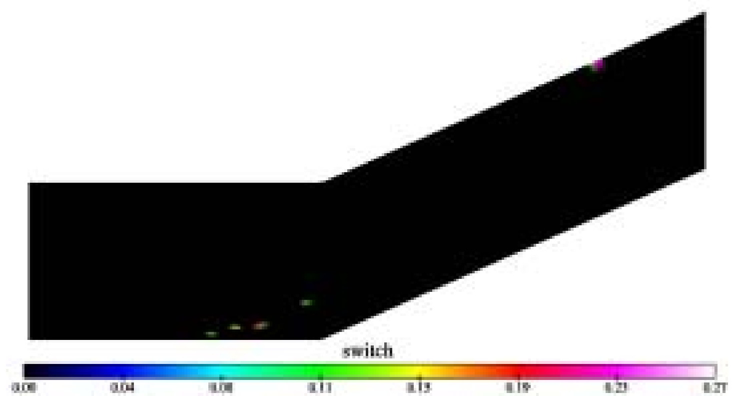
Mean skin-friction on the wall (24˚)



Pressure distribution on the wall (8˚)



Instantaneous contours in the flow field (24˚)



Instantaneous contours of switch in the mid spanwise plane

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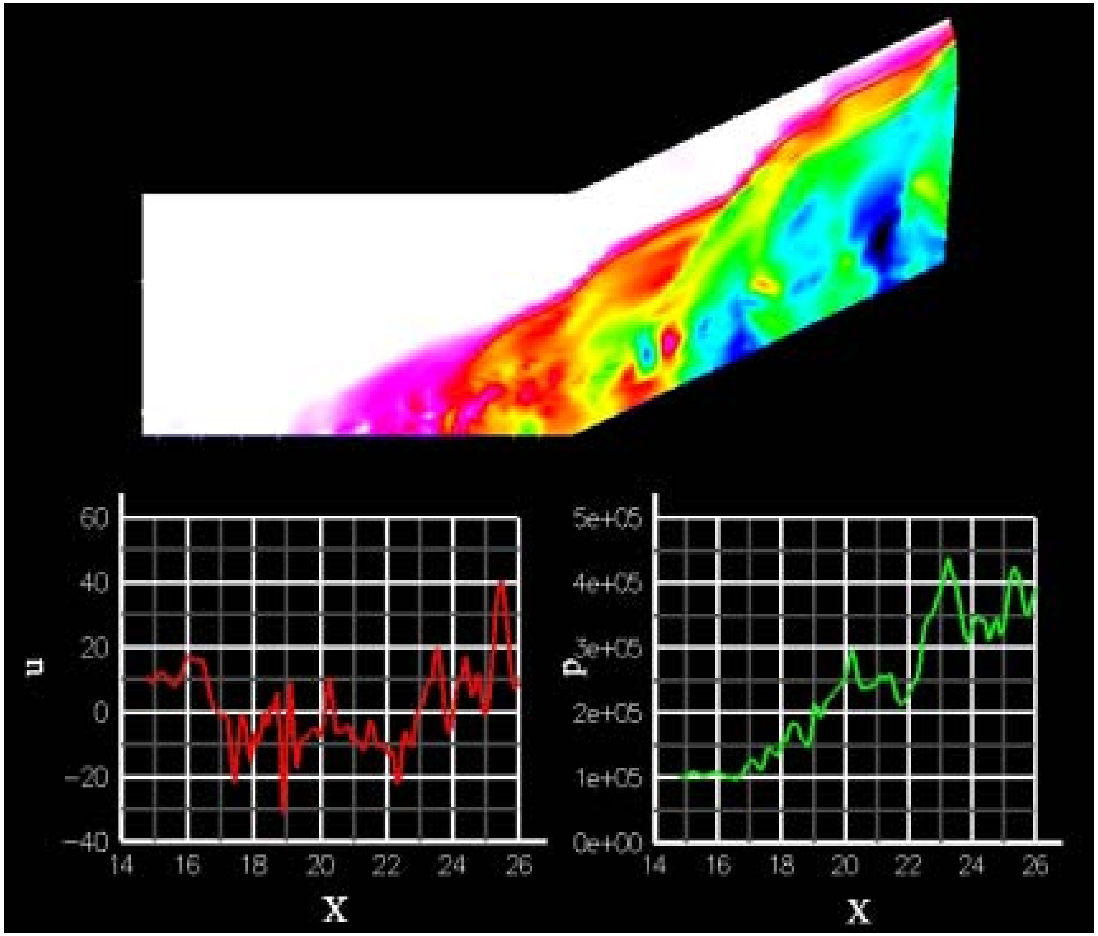
LARGE EDDY SIMULATIONS : COMPRESSION CORNER FLOWS



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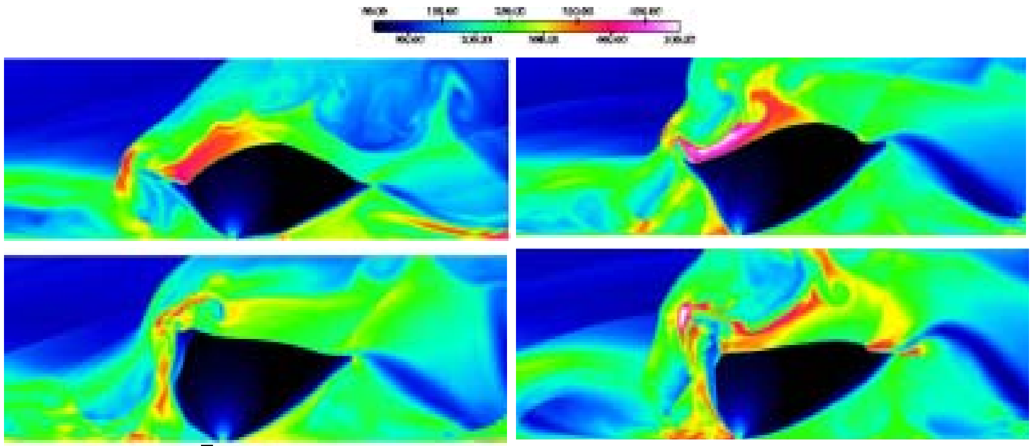
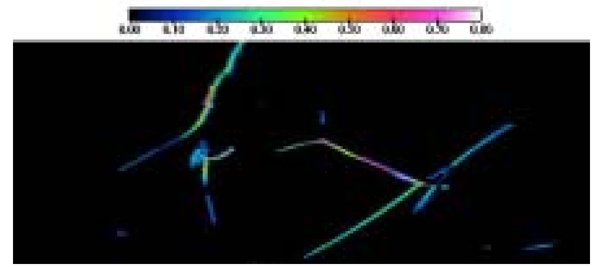
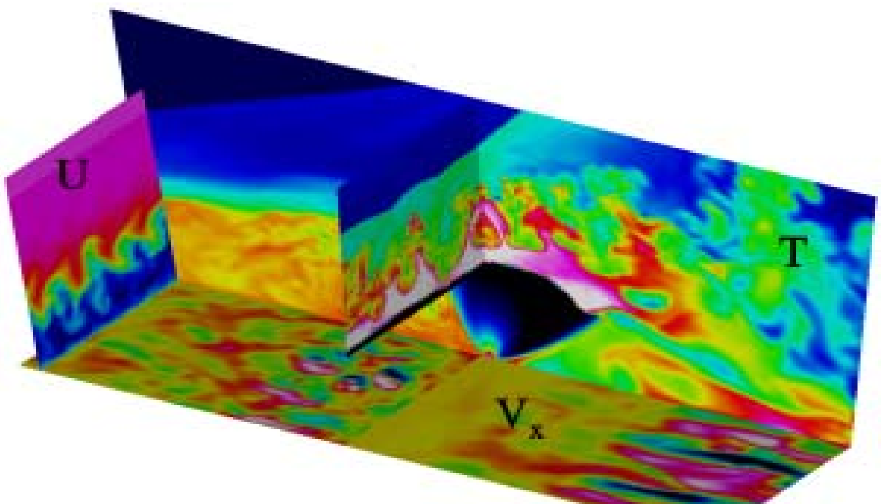
LARGE EDDY SIMULATIONS : LATERAL DIVERT JET FLOWS



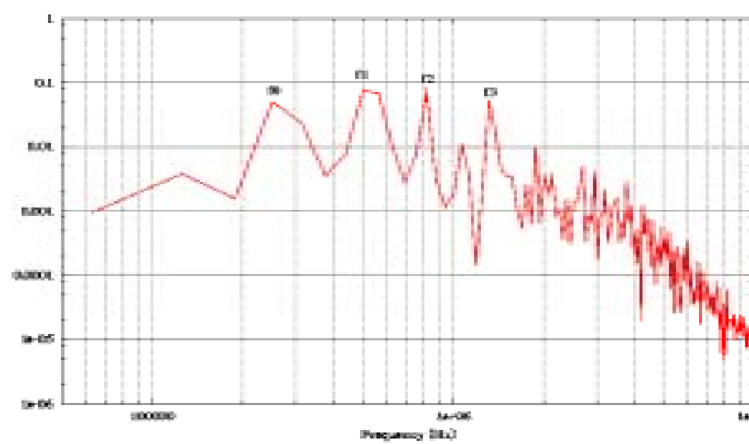
Instantaneous temperature contours



Instantaneous switch contours



Instantaneous contours for the 3D transverse jet



Turbulent kinetic energy spectrum for the boundary layer

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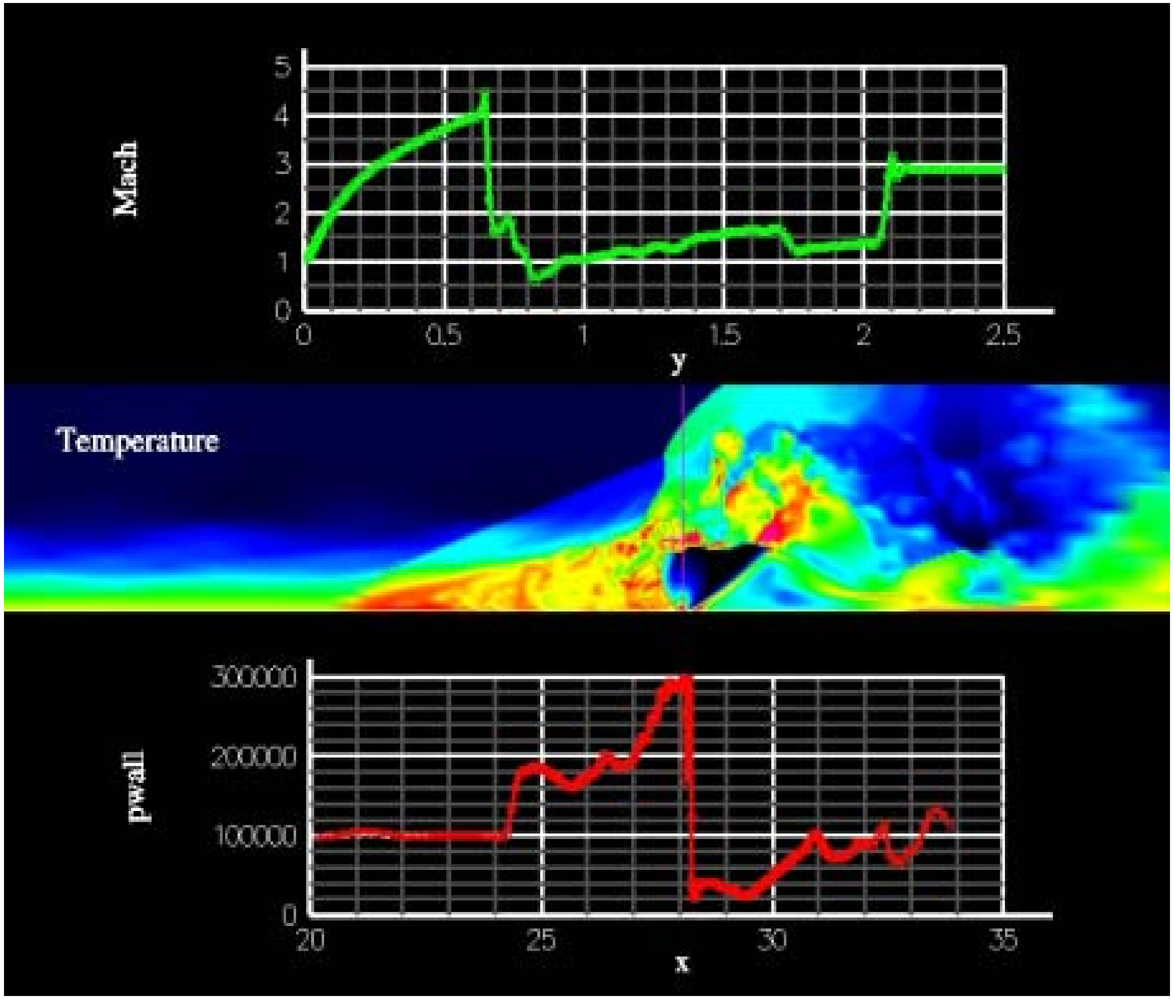
LARGE EDDY SIMULATIONS : LATERAL DIVERT JET FLOWS



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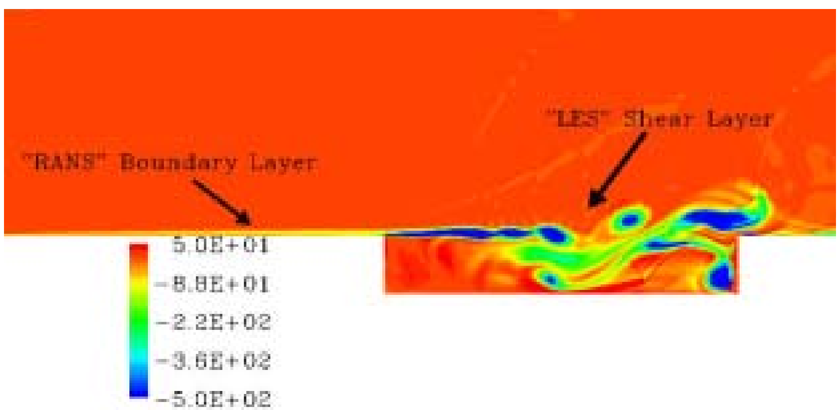
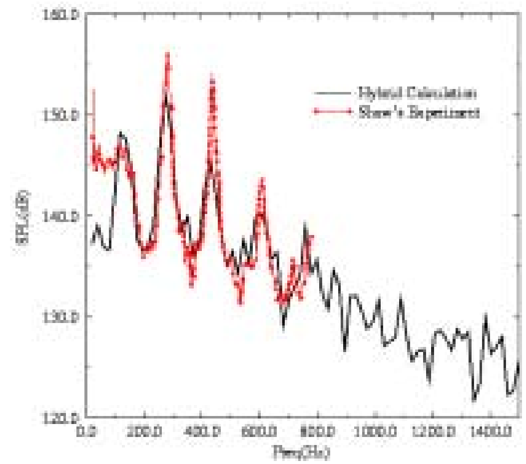
LARGE EDDY SIMULATIONS : CAVITY FLOWS

- Predictions of Dynamic pressure loads
  - Store separation problems
  - Fatigue due to dynamic loading
  - Major observations
    - Steady “RANS type” upstream boundary layer
    - Highly unsteady “LES type” shear layer over the cavity
    - Large oscillations in all flow variables in the shear layer
  - Hybrid RANS-LES Modeling



Contours of Vorticity



Comparison of Dynamic Load Predictions with Experimental Data.

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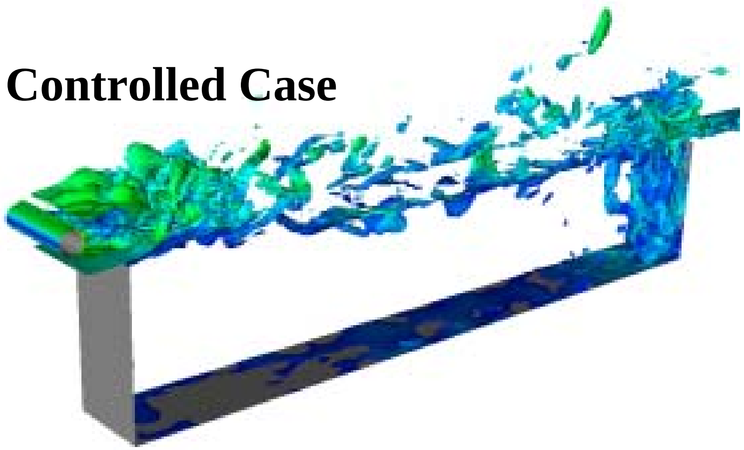
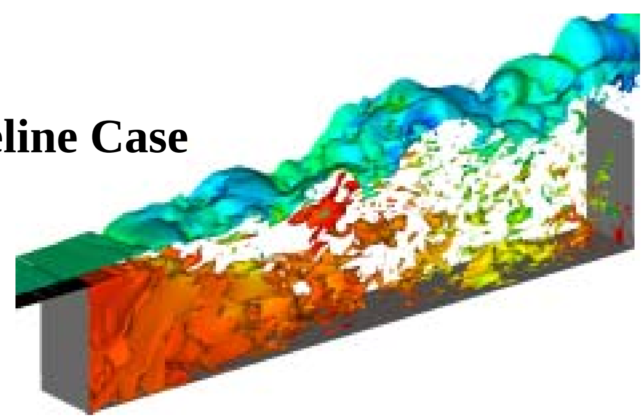
LARGE EDDY SIMULATIONS : CONTROL OF CAVITY FLOWS

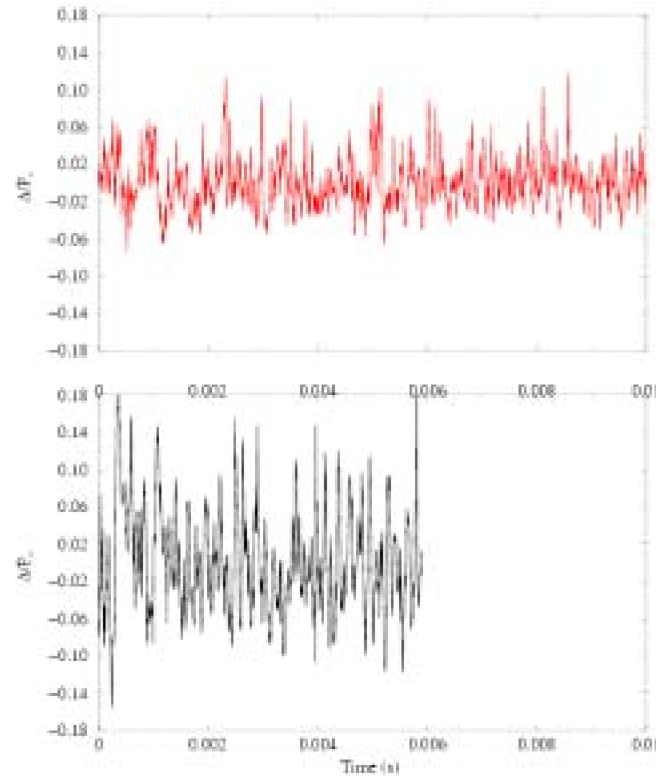
- LES of controlled cavity flows
  - Need to understand control mechanisms

Controlled Case



Baseline Case





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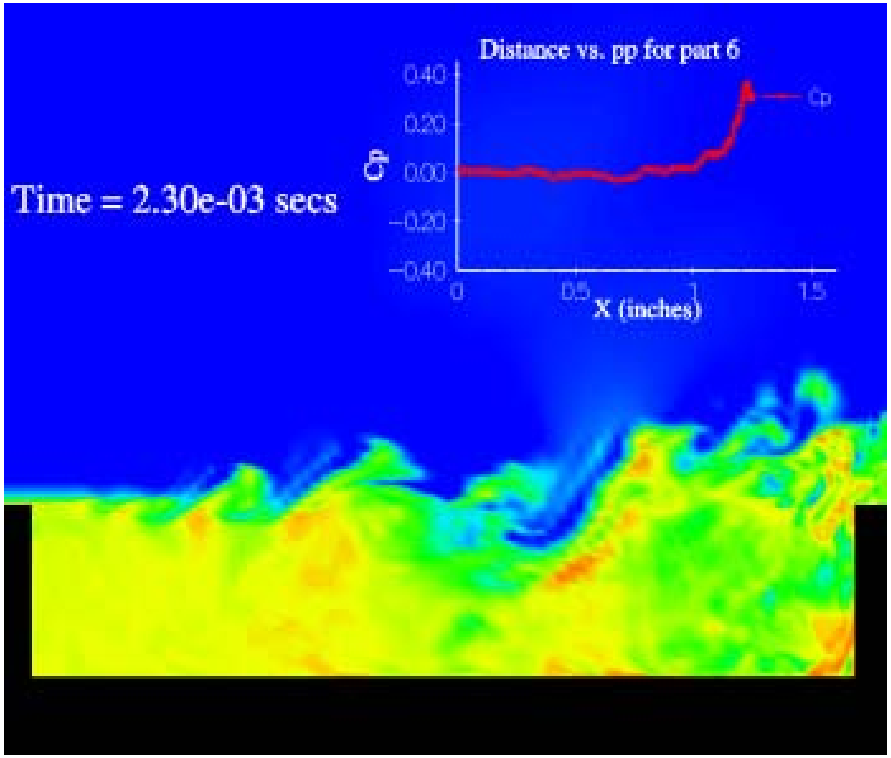
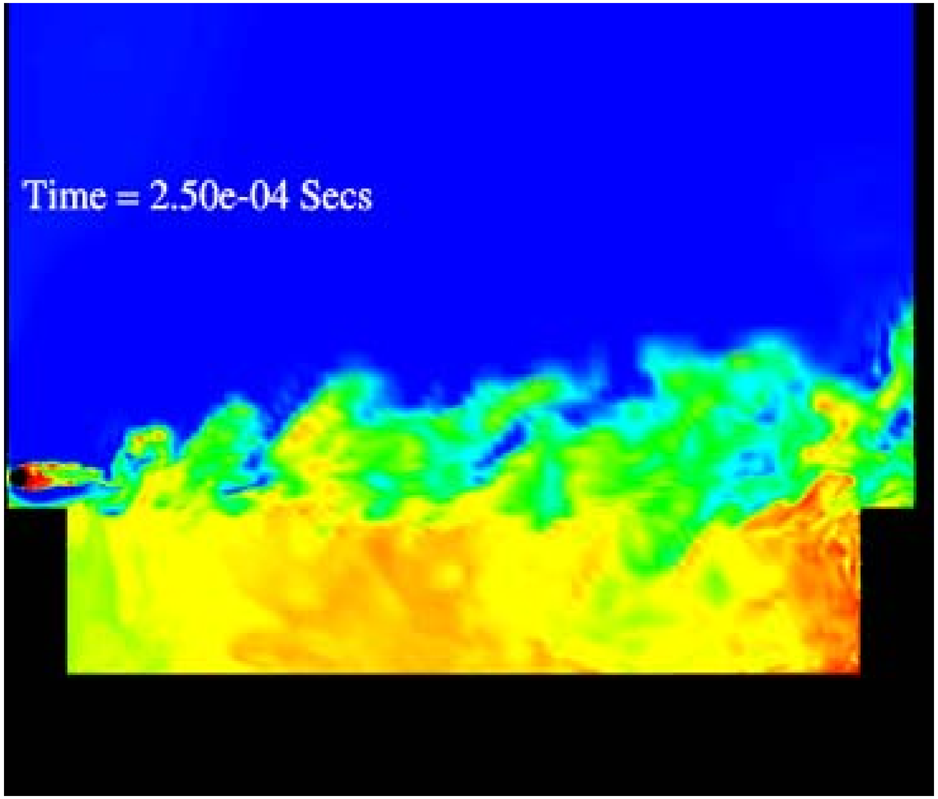
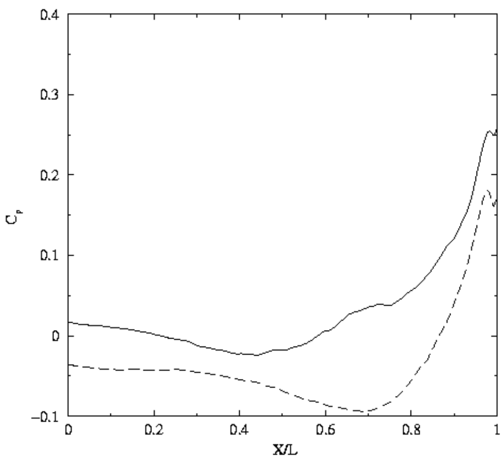
LARGE EDDY SIMULATIONS : CONTROL OF CAVITY FLOWS



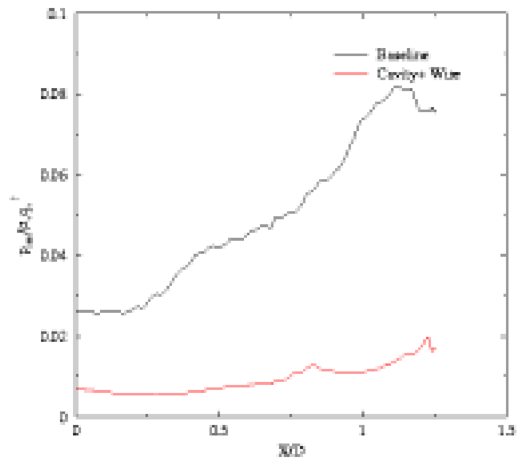


Baseline Flow Field **Controlled Flow Field**

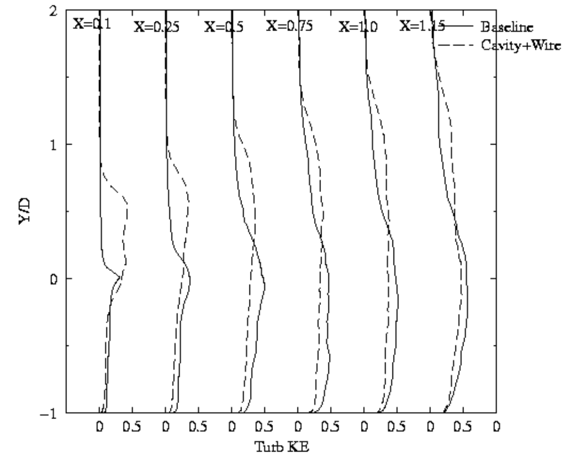
LARGE EDDY SIMULATIONS : CONTROL OF CAVITY FLOWS



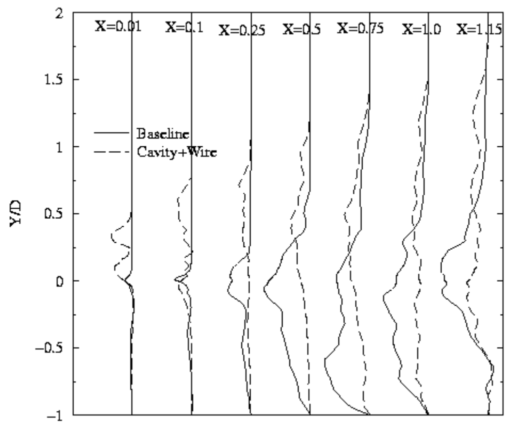
Static Loads



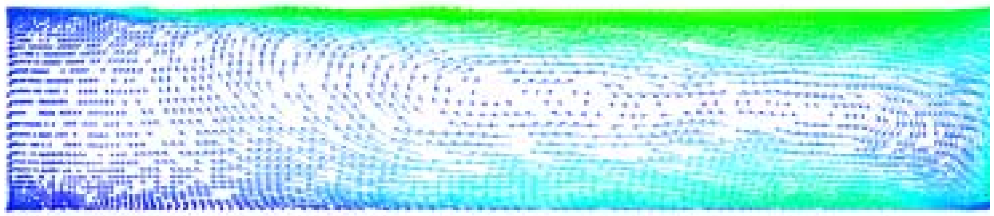
Dynamic Loads



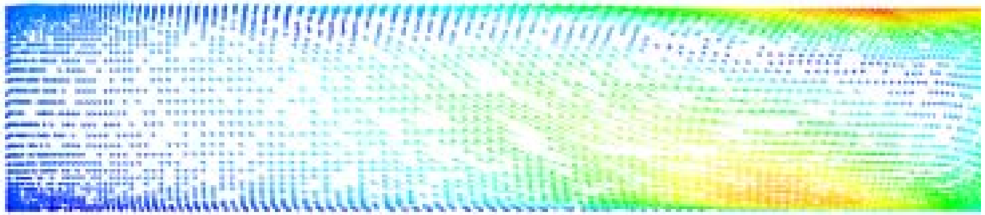
Turbulent KE Distribution



Reynolds Stresses



Baseline Case



Controlled Case

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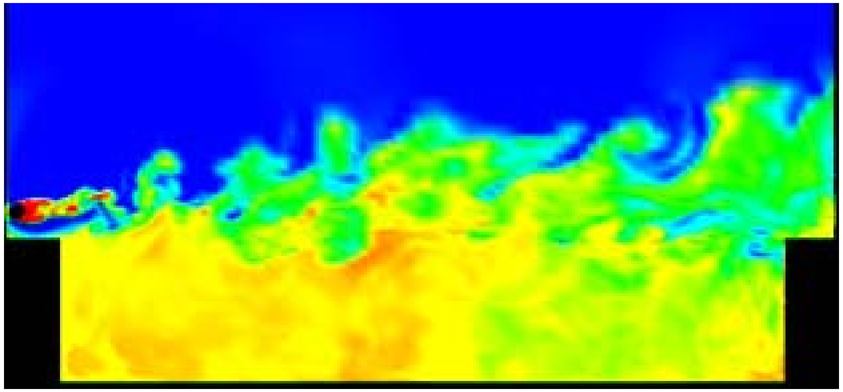
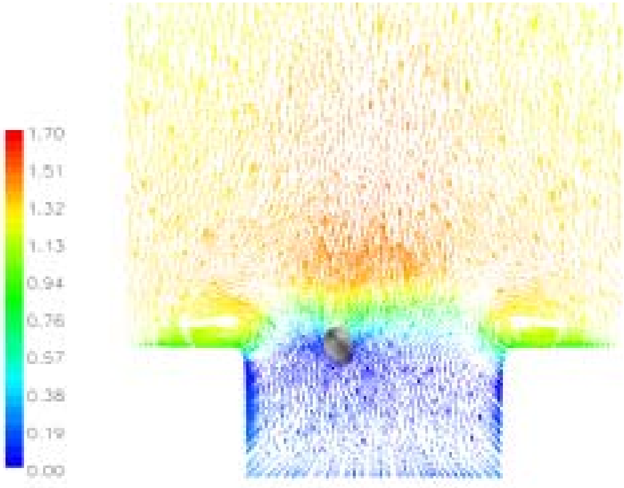
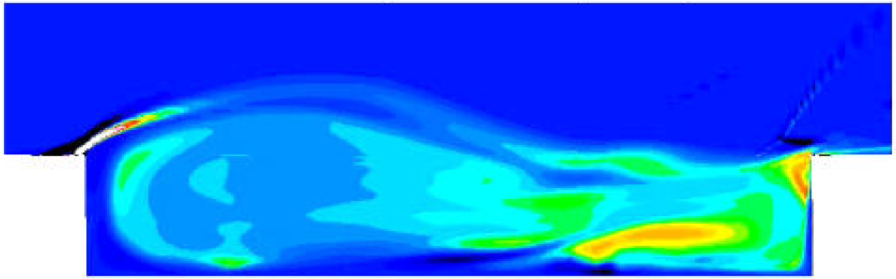
LARGE EDDY SIMULATIONS : CONTROL OF CAVITY FLOWS

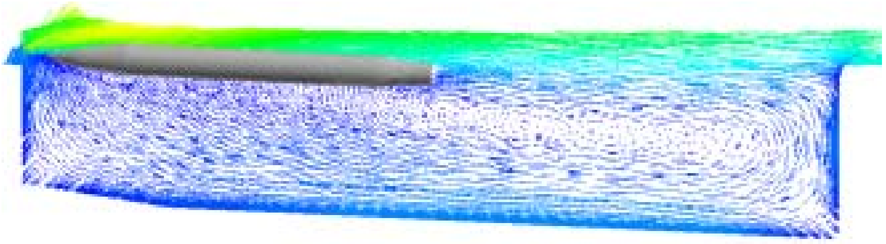


Passive Control





Active Pulsed Blowing Control



Effect of Control on Store Separation

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PROPER ORTHOGONAL DECOMPOSITION

- Introduced by Lumley (1967)
  - Decomposition based on mean-square (optimal)
  - Leads to an Eigen-value problem whose solution yields an optimal representation of the flow field
- POD Based Dynamical Model
  - Eigenfunctions written as linear combination of the instantaneous field

$$\phi_i^n(\vec{x}) = \sum_{k=1}^{M} \psi^n(t_k) u_i(\vec{x}, t_k)$$

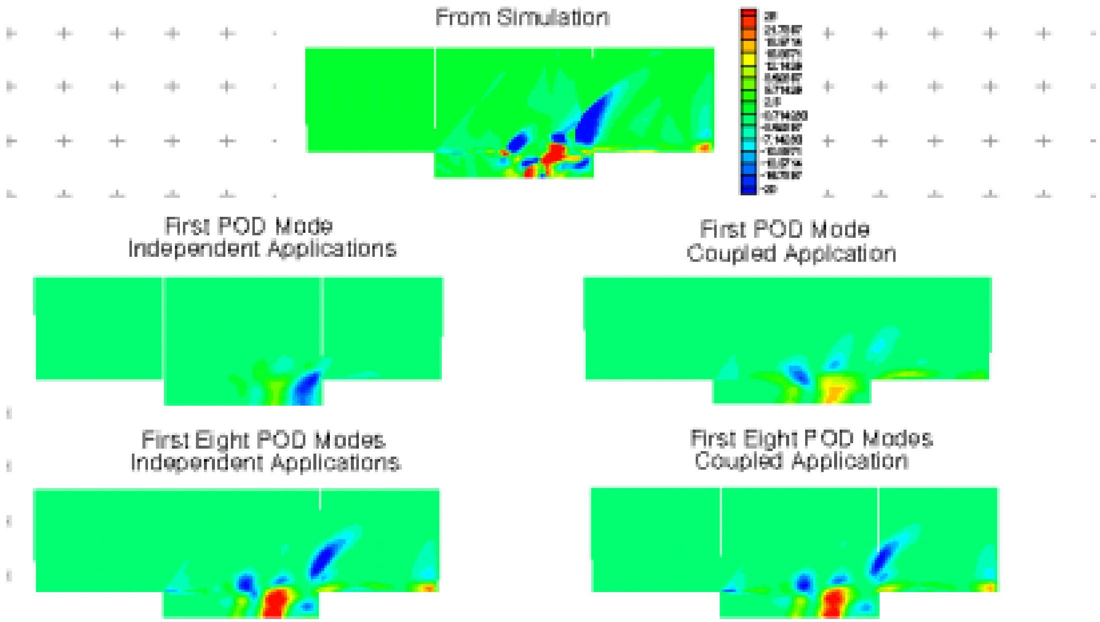
  - $u_i=(u(x_1,t_i),u(x_2,t_i), \ldots , u(x_N,t_i))^T$; ψ is the Eigen-solution of the M x M matrix (M=Ensemble Size)

$$C_{kl} = \frac{1}{M} \int_D u_i(\vec{x}, t_k) u_i(\vec{x}, t_l)$$

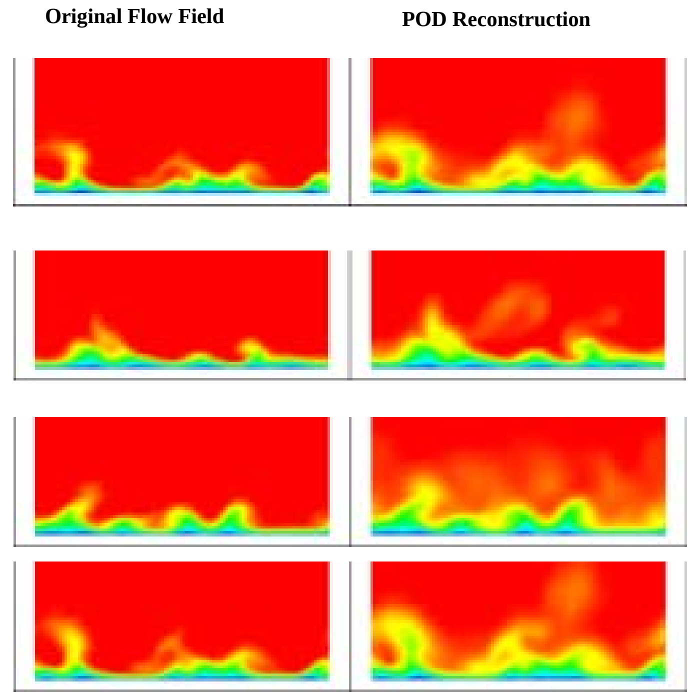
  - Known as the Snapshot method
  - A simple Galerkin projection on to the NS equations allows user to play-back flow field at a fraction of the cost of LES
    - ideal for studies of control system parameterics

PROPER ORTHOGONAL DECOMPOSITION

Cavity Flow



Boundary Layer Flow



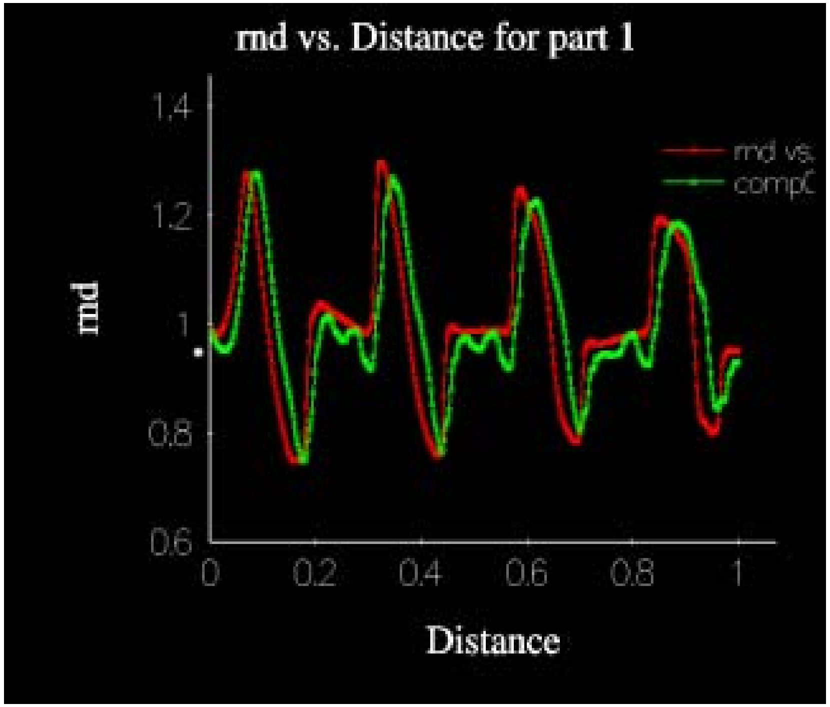
U-Velocity

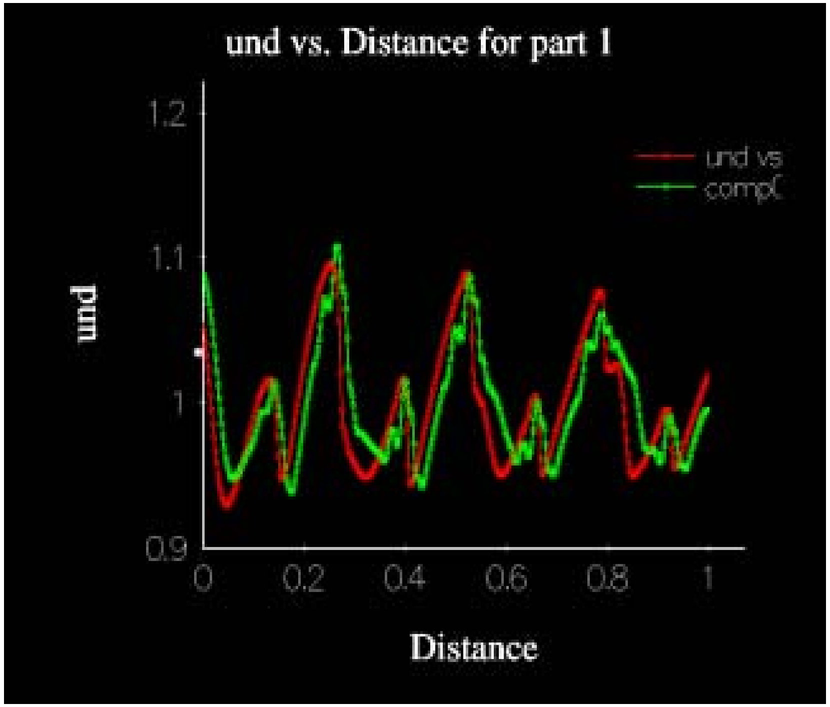
- **POD Applications :**
  - Model Analysis
    - Yields detailed information about different phenomena governing flow evolution
  - Dynamical modeling
    - Recreated flow field can be used to prescribe BCs for other simulations
    - Control system studies to experiment with control strategies

PROPER ORTHOGONAL DECOMPOSITION

Replaying Time Accurate Datasets :

One-Dimensional Example





Non-Dimensional Density

Non-Dimensional Velocity

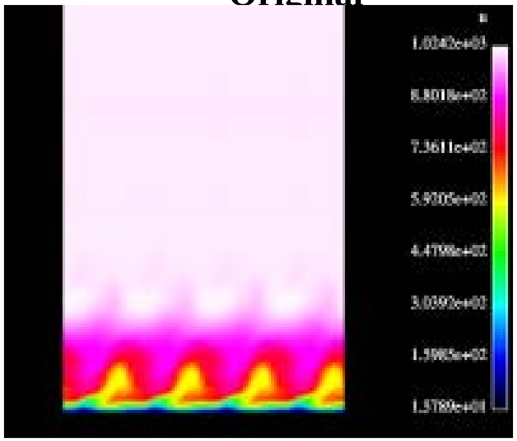
PROPER ORTHOGONAL DECOMPOSITION

Replaying Time Accurate Datasets :

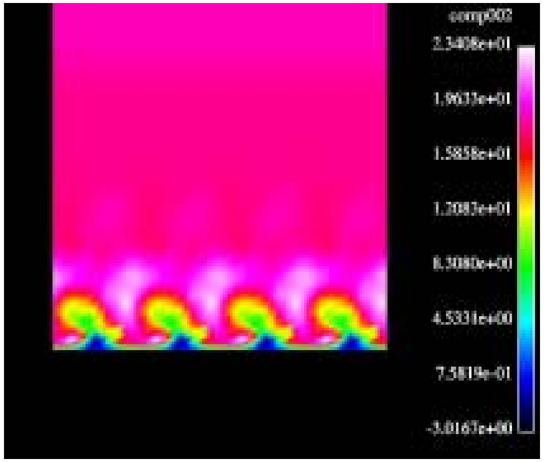
Two-Dimensional Example

Axial Flow Velocity

Original

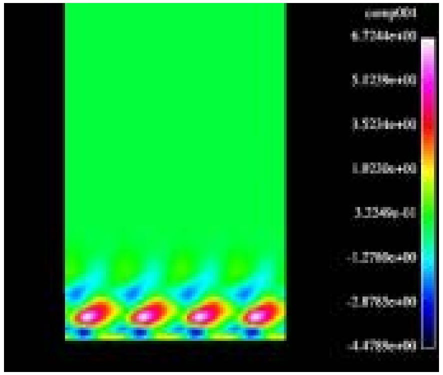


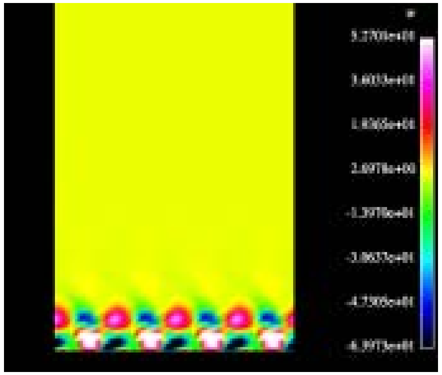
Recreated



Transverse Flow Velocity

Original





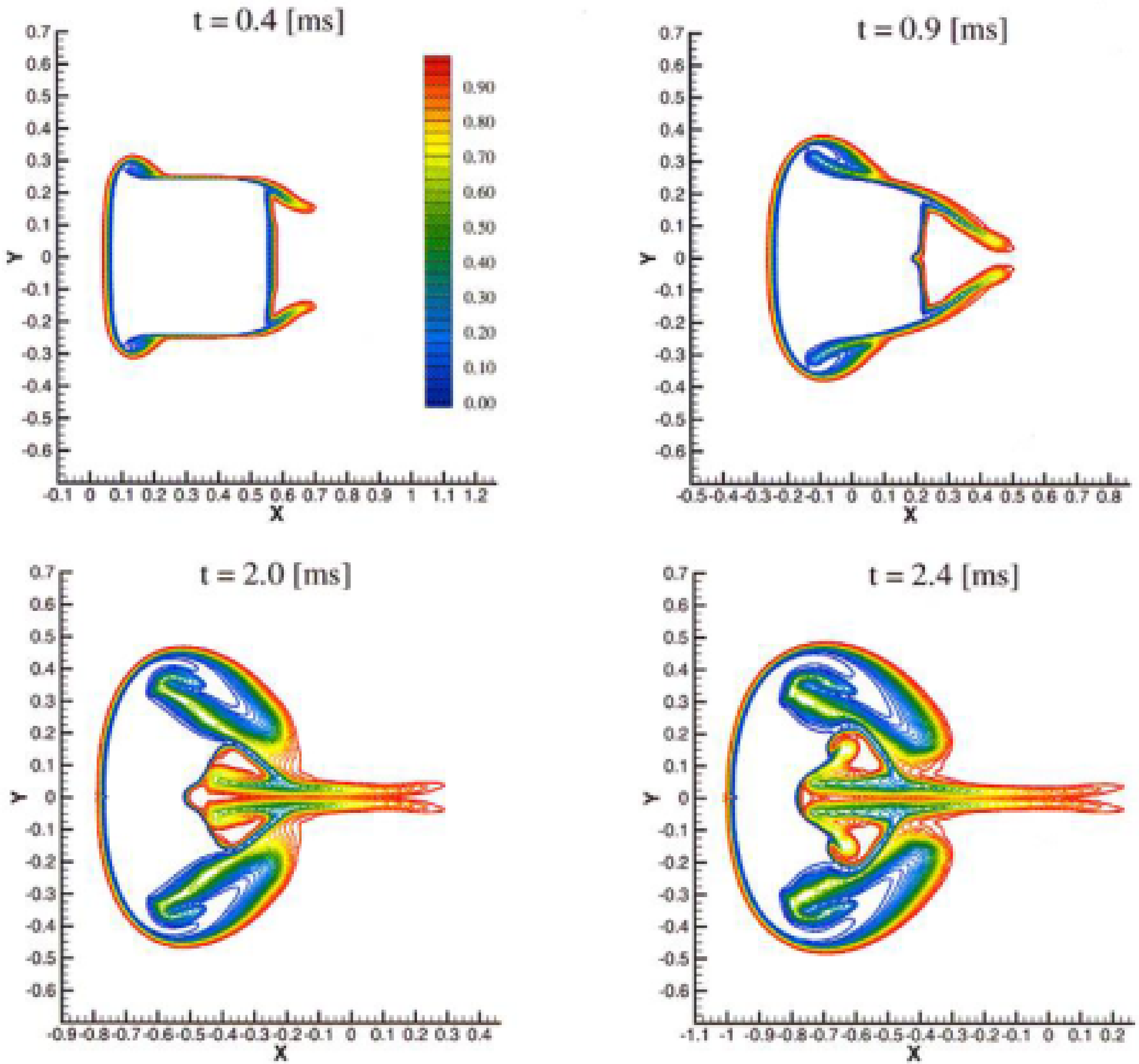
HIGH SPEED GAS/LIQUID METHODOLOGY

- **Interfacing capturing scheme**
  - **Numerical procedure integrates through interface**
- **Physical equations of state given to each phase**
- **Acoustic characteristics of multi-phase mixture resolved accurately**
  - **Critical for pressure/blast wave interaction with liquid interface**

GAS/LIQUID TEST PROBLEM

- Evolution of cylindrical pellet of liquid that gets released from missile
  - Liquid blob flying at Mach 2 initially
  - Strong aerodynamic interactions with surrounding atmosphere (shock wave generated ahead of liquid blob)
  - Droplets stripped from liquid to form a dens spray

FREE FLIGHT OF A CYLINDRICAL PELLET OF FLUID
CONTOURS OF GAS MASS FRACTION



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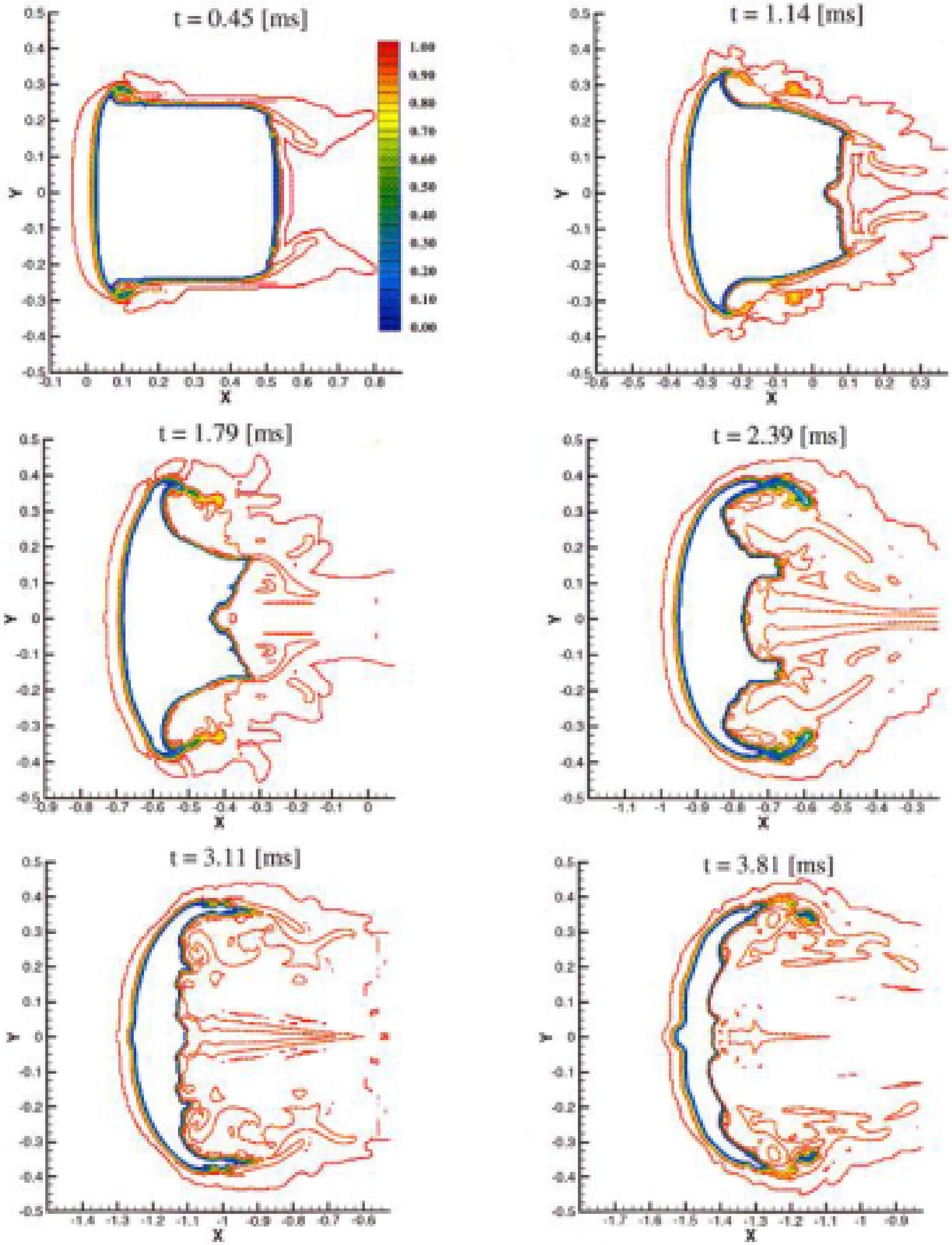
FREE FLIGHT OF A CYLINDRICAL PELLET OF FLUID

BREAKUP WITHOUT TRACKING OF THE BROKEN MASS



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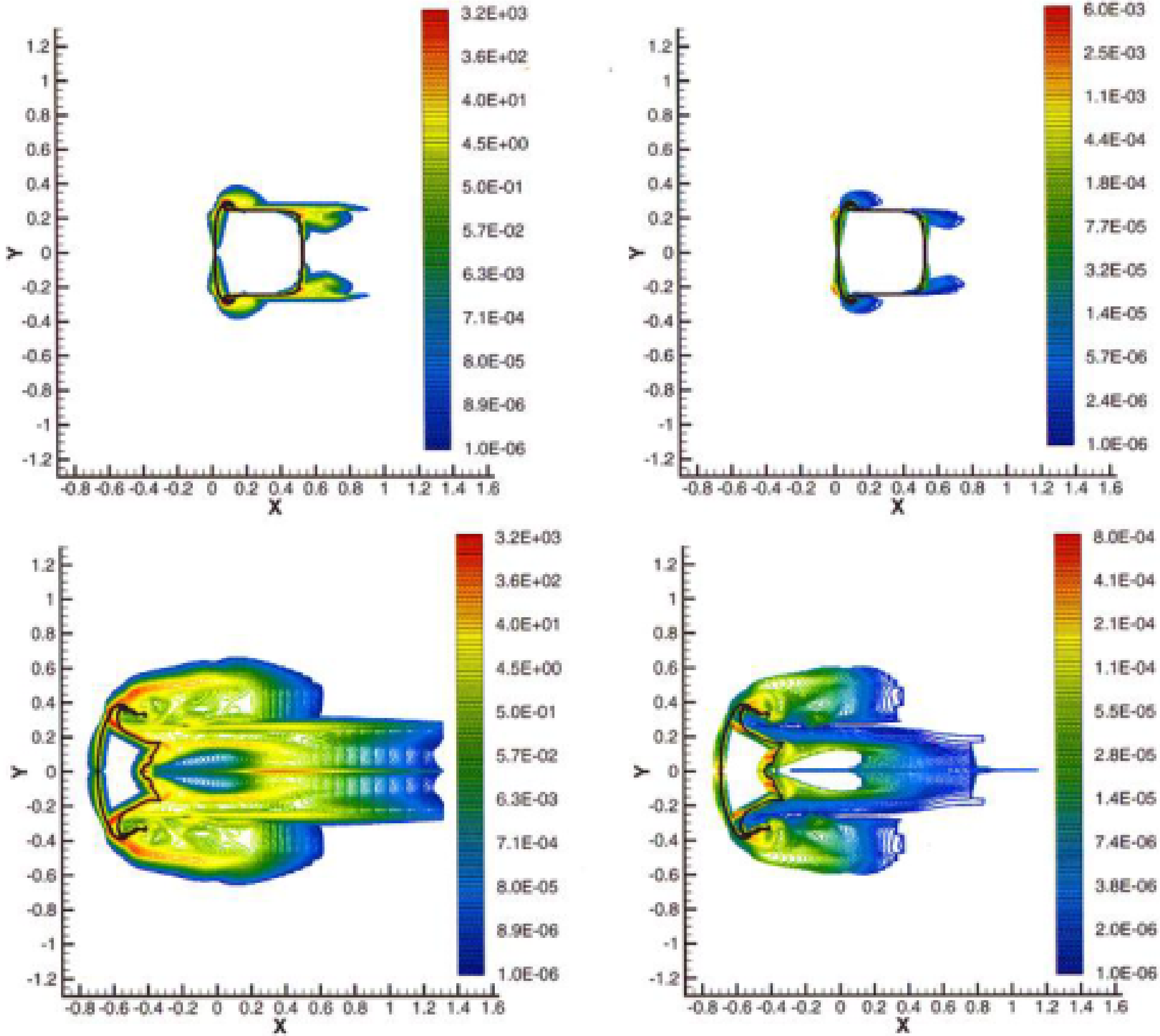
FREE FLIGHT OF A CYLINDRICAL PELLET OF FLUID

BREAKUP WITH EULERIAN TRACKING OF THE PARTICULATE CONTINUUM



CRAFT Tech

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